Stochastic Radiative Transfer on Modeled Cloud Fields

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Abstract—**Several efforts are currently underway to improve cloud-radiation parameterizations in Global Climate Models (GCMs) by incorporating statistical properties of the cloud field. Although some radiation parameterizations, which are already computationally costly, now incorporate subgrid scale variability in cloud properties, they are not yet capable of using this information in their calculations of the 3-D radiation fields. Before drastic changes are made to such algorithms to incorporate cloud–cloud radiation interactions, the impact of including realistic high-resolution cloud distributions on the shortwave fluxes should be assessed. This letter provides a framework for carrying out such assessments, including a new methodology that blends a stochastic radiative transfer model, high-resolution cloud fields from a mesoscale meteorological model, and a threshold and object identification technique applied to cloud water content fields. This process provides a link between the radiative fluxes calculated in GCMs, where clouds occur at a subgrid scale, and the highly resolved cloud fields in a regional climate model, which can provide cloud field statistics. Two case studies are described herein.**

Index Terms—**Clouds, stochastic radiative transfer (RT).**

I. Introduction

DEFICIENCIES in cloud parameterizations for Global Climate Models (GCMs) are perhaps the most-cited source of model bias and uncertainty (e.g., [1]–[5]). The challenge in creating modern cloud parameterizations that give accurate results across a wide range of conditions and climate regimes is that the underlying dynamical processes that result in cloud formation are unresolved at current GCM grid scales. This gravely impacts many important physical processes including radiative transfer (RT) and precipitation which are nonlinear with respect to condensate amount. RT through a broken or complex cloud field are classic scenarios with which current climate models struggle. For example, Norris and Weaver [6] attributed the overprediction of cloud-top height and cloud optical thickness for extratropical oceanic clouds in the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM3) to heterogeneity in the cloud field induced by unresolved spatial variability in vertical motion.

Many current GCMs account simplistically for some effects of unresolved cloud spatial variability, by tuning the cloud water amount input to the model radiation code, diagnosing cloud fraction as a function of a subsaturated, grid-cell mean relative humidity, or carrying out microphysical calculations separately for the stratiform and convective portions of the cloud field. However, the chosen methods and parameters are frequently unrelated to the dynamics which control cloud variability. These simplifications lead to deficiencies in other modeled quantities such as atmospheric heating and moistening rates. Such errors then propagate through the simulated climate by forcing compensation in other components of the energy and water budgets, leading to incorrect cloud-climate feedbacks over time.

There are three basic strategies for developing more accurate fine-scale cloud variability within climate models. First is the ongoing trend across all aspects of climate research toward use of higher resolution models, either GCMs or limited-area mesoscale models, for process, sensitivity, and prediction studies. Second is the "superparameterization" methodology, in which very high-resolution submodels of convection and other cloud-producing processes are embedded within an otherwise coarse-resolution GCM [5]. Third is the practice of explicitly predicting the subgrid distributions (e.g., variance, skewness) of quasi-conserved variables like total water content (water vapor plus cloud liquid and ice) inside each GCM grid cell from the GCM-resolved fields, i.e., the so-called "statistical cloud schemes" [7]–[9]. Within such a framework, quantities like fractional cloud cover inside a model grid cell can be diagnosed, for example, by integrating over the supersaturated portion of the cloud water distribution. Still, an improved understanding on how cloud variability can be predicted from GCM-resolved variables is required, including a deeper understanding of the dynamical and thermodynamical mechanisms that produce such variability (see [10] and [11]). Indeed, as the ability to generate more realistic model cloud fields increases, the impact of spatially variable cloud fields on processes such as atmospheric RT must also be better quantified. Radiation and microphysical schemes are already some of the most computationally expensive components of most climate models, so objective methods are needed for evaluating where these gains in model sophistication and complexity will yield the best results in terms of improved climate simulations.

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We conceptualize a logical framework for systematically investigating when cloud field complexity matters for RT. In other words, what type of cloud scenes (linked to dynamical regime) will yield different answers in the simulated radiation? Answering this question systematically involves intercomparisons among levels of increasingly sophisticated treatment of cloud-radiation interactions.

1) *Level 0*—GCM Simple: Plane parallel RT carried out on the average cloud water and cloud fraction in the domain (or GCM grid cell) of interest.
2) *Level 1a*—Independent Column Approximation: Plane parallel RT carried out individually on all the "subgrid pixels" in the GCM grid cell or coarse-resolution domain of interest, neglecting between column photon transport [12].
3) *Level 1b*—Stochastic: RT using domain average statistics (i.e., not working with individual subgrid pixels) in the GCM grid cell or coarse-resolution domain of interest, accounting for cloud–cloud photon interactions.
4) *Level 2*—Full Statistical: RT using 3-D cloud field pdfs from a high-resolution model.

This letter summarizes our initial efforts to explore this framework and identify a path forward for more comprehensive future treatments. The main focus is our development of a methodology to compare the Level 0 and Level 1b stages for a given set of cloud scenes [the Level 0/Level 1a intercomparison is a more straightforward problem and has been explored (e.g., [13])]. We accomplish this by blending three things into an idealized strategy: quasi-realistic model cloud fields produced by high-resolution simulations with a mesoscale meteorological model; a stochastic RT model able to account for subgrid-scale cloud statistics and cloud properties; and, to link the two, image processing techniques similar to those used in satellite remote sensing of cloud fields. Taken together, these three pieces allow us to mimic some of the interactions that might take place inside a next-generation GCM containing both realistic subgrid-scale cloud variability and a more advanced radiation scheme that can account for this variability.

Our purpose here is to frame the problem of assessing tradeoffs associated with increasing the complexity of cloud-radiation interactions inside GCMs and propose one methodology for carrying out such assessments. Therefore, the results we show are intended only as preliminary illustrations of this technique and these concepts, to provide a foundation for more comprehensive future investigations.

II. Model Description

A. Stochastic Model

A statistically based radiation scheme, such as the stochastic model briefly described below, when coupled inside a GCM to a statistically based cloud water scheme offers improved RT accuracy for a marginal computational cost (compared to approaches that explicitly model cloud fields) making it a logical choice for this letter. The offline RT model used here, DSTOC (see [14]–[18] for details), consists of a spectral model with 38 bands and a 32-layer atmosphere. The extinction processes include gaseous absorption, cloud scattering and absorption, and isotropic Rayleigh scattering using up to 16 streams. The effect of cloudiness is parameterized in terms of cloud water content (CWC) and the geometry of the cloud field is described by combining a characteristic horizontal scale for the clouds (in these cases, ellipses) with the assumed Markovian cloud distribution to generate a distribution of chord lengths. This chord length distribution controls the probability that a photon has of traversing any of the cloudy segments when passing through the cloud field. The clear sky is described in a similar manner.

Traditional RT schemes used in GCMs consider two situations: the photon is either in a cloud or not. The mathematical description in DSTOC allows for two additional states where the photon is transitioning from cloud to clear sky or vice versa [18], and the spectral model solves a planar RT equation including these states. It is then possible to estimate the heating rates through a complex cloud layer, accounting for horizontal transport of photons within and among clouds. This additional capability admits a larger role for cloud geometry. Thus, over domains on the order of a GCM grid cell, along with a statistical accounting of variable extinction, it is expected to significantly increase the accuracy of radiative fluxes for scenes with broken or inhomogeneous clouds over those computed using the more simplistic, plane-parallel homogeneous schemes currently employed in many GCMs [15]. Input parameters include mean cloud-base and cloud-top heights, mean total cloud water path, effective radius, cloud fraction, and solar zenith angle. These parameters, combined with the chord length distribution, are used to derive a probability distribution of volume extinction coefficients. The output of DSTOC is the ensemble-average radiative flux over the whole horizontal domain at each atmospheric layer, for each band. Although the cloud properties are homogeneous within each region of cloud, they can vary among model layers in terms of cloud field geometry and cloud microphysical properties. In this way, the situation of cumulus or stratocumulus clouds under cirrus clouds, which occurs often in nature, can be simulated. Evaluation of DSTOC using observed cloud and radiation data is described in [20]. DSTOC has not yet been bench-marked against Monte Carlo simulations but has been compared extensively to plane-parallel radiation codes [15], [17]–[19].

The key step in blending the three elements of our approach is to derive the various input parameters for DSTOC directly from the "realistic" cloud fields produced by high-resolution simulations with a mesoscale atmospheric Conceptually, these high-resolution cloud fields embody the kind of cloud spatial variability that might be characteristic of what future GCMs could represent. We describe these shortly.

B. Plane Parallel RT Model

The Column Radiation Model (CRM) is representative of SW RT codes used in many present-day atmospheric GCMs. The CRM is a standalone version of the plane-parallel RT code employed in the NCAR CCM3 [21]. The CRM utilizes the Delta–Eddington approximation [22] to solve the RT equation. The SW spectrum is divided into 18 unequally spaced bands with wavelengths ranging from 0.2 to 5.0 μm and includes absorption by ozone, carbon dioxide, water vapor, and oxygen, as well as clouds. Molecular scattering is included along with scattering from clouds and aerosols, with isotropic scattering assumed between vertical layers. McClatchey climatological profiles [18] of temperature, carbon dioxide, water vapor, and ozone are specified at 32 unequally spaced vertical layers for the U.S. standard atmosphere.

III. High-Resolution Model Cloud Scenes

In this letter, we use the Regional Atmospheric Modeling System (RAMS) [23] to generate the cloud scenes whose statistics are used in the RT calculations. Briefly, RAMS solves the full nonlinear nonhydrostatic equations of motion for the atmosphere in a terrain-following coordinate system, and it includes multiple parameterization options for subgrid-scale transport, RT, convection, and land-surface processes. It also includes a suite of highly sophisticated representations of cloud and precipitation microphysics that are prognostic for all resolved processes in both mixing ratio and number concentration for six microphysical species (rain, pristine ice, snow, aggregates, graupel, and hail) and prognostic in mixing ratio only for cloud liquid water [24], [25].

For the analysis described here, input parameters for DSTOC are derived from simulations of storms observed over the DOE ARM Southern Great Plains (SGP) site during the March 2000 Intensive Observing Period. These simulations are described in detail in [2], and the evaluation of these simulated clouds against ARM observations illustrates the high degree of realism achieved via this use of RAMS at high resolution. Each simulation used two nested grids, both centered on the SGP site. The outermost (Grid 1) covers approximately $2200 \times 2200\ \text{km}^2$, with 12-km horizontal grid spacing, on which NCEP reanalysis boundary conditions are assimilated. The domain of interest (Grid 2) covers $750 \times 750\ \text{km}^2$ with 3-km horizontal grid spacing. This domain corresponds to the area covered by several typical GCM grid cells, but simulated with high enough resolution so that convection is not parameterized but instead is explicitly simulated. While computationally expensive, this combination of high resolution and relatively large domain size enables us to characterize the sub-GCM-grid-cell statistics of dynamic, thermodynamic, and cloud variables, and their link with the large scale.

Two storm periods during the IOP were simulated: March 2–3 and March 7–8, 2000 [Fig. 1(a) and (b)]. Both experienced well-developed cyclones with different amounts of cloudiness and cloud variability over the SGP site, thus providing a broad range of highly variable cloud scenes. In some sense, the kind of cloud variability in these runs previews the variability that a next-generation GCM might be able to capture. Here, we chose two time slices from the larger body of model output: 0200Z on March 3, a relatively heterogeneous, frontal scene with a variety of cloud types; and 0400Z on March 7, a relatively homogeneous, prefrontal stratocumulus scene. In addition, as a supplementary analysis, we explored the impact of model horizontal resolution on the cloud fields and the stochastic radiative fluxes for the March 2–3, 2000 storm period, using results from RAMS runs with horizontal grid spacings of 10, 20, 40, 80, and 160 km [11]. This is particularly relevant to the question of what information about the subgrid cloud variability a GCM should provide to the model radiation scheme. For example, it should yield insight about the resolution needed to provide the correct level of detail to the stochastic model in terms of chord lengths.

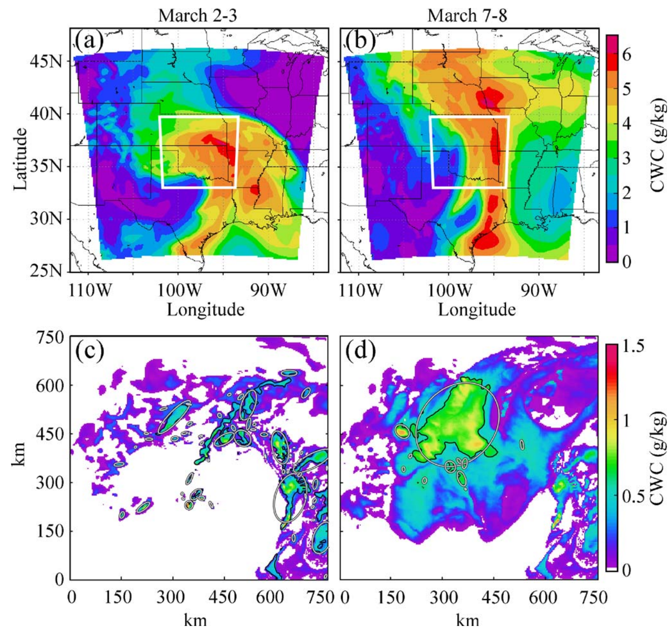

Fig. 1. CWC at 3900 m from the (a) March 2–3, 2000 and (b) March 7–8, 2000 storms simulated by RAMS in Grid 1. The white line shows the areas covered by Grid 2. (c) Grid 2 for March 3, 2000 at 0200Z. The black line shows the contour where the CWC is at the given threshold of 0.3 g/kg. The ellipses are the fit to the closed contours. (d) Same as (c) for March 7, 2000 at 0400Z and for a CWC threshold of 0.6 g/kg.

Next, we describe the methodology we developed to import statistical information about these RAMS-simulated cloud scenes into DSTOC and CRM for the plane parallel calculations, the various tests of our system we conducted, and our findings.

IV. Image Processing, Derivation of Cloud Statistics, and Preliminary Findings

There were (and remain) a number of challenges in turning output from RAMS into meaningful input for DSTOC. Dealing with these challenges is instructive, as they are a preview of issues that would arise if one were to attempt to capture the capabilities of a stochastic radiation scheme with suitable parameterizations inside a climate model.

For these preliminary analyses, the CWC, cloud base height, and cloud thickness of single model cloud layers is imported from RAMS into DSTOC (Table I). From the RAMS domain, we extract a horizontal cloudy layer from which we derived input statistics and parameters for DSTOC and CRM. Cloud horizontal scale is determined from the CWC field [Fig. 1(a) and (b)]. First, a CWC threshold is applied, and areas exceeding the threshold identified. Next, ellipses are fit to these closed, irregularly shaped areas as somewhat idealized representations of the clouds [Fig. 1(c) and (d)]. Ellipses are selected to approximate the cloud shape because they are a convenient way of recognizing spatial coherence for defining individual cloud "objects." It allows identification of coherent structures in a high-resolution cloud field and easy derivation of statistics from the collection

TABLE I
GENERAL PROPERTIES OF THE CLOUD FIELD FOR CASE STUDIES

Date	March 3, 2000	March 7, 2000
Solar Zenith Angle	44.8 deg	44.8 deg
Cloud Base Height	3.74 km	1.28 km
Cloud Thickness	379 m	163 m
Cloud Water Content	0.05 g/kg	0.15 g/kg
Domain size	750x750 km^2	750x750 km^2
Resolution	3 km	3 km
R_{eff}	7 μm	7 μm

of objects. This approach also matches precisely with the mathematics of DSTOC. Finally, cloud fraction and the distribution of cloud chord lengths (along with the mean CWC, cloud base, and cloud thickness) are calculated as necessary input parameters to DSTOC from the distribution of ellipses in the layer. Ellipses are treated individually and given equal weighting.

The water content threshold and ellipse techniques provide us with two ways of calculating cloud fraction which can either be based on ellipse area (EA), or the pixel area (PA) of the irregularly shaped closed contour of fixed CWC [Fig. 1(c) and (d)]. The characteristic chord length also can be estimated from the equivalent diameter of the ellipse or that of the closed shaped contour. The DSTOC and CRM RT calculations were performed using all four combinations of these two characteristics. In addition, we varied the CWC threshold over a wide range and examined the changes in the cloud scene, the ellipses, and associated statistics generated, and the resulting radiative fluxes found. The mean difference in cloud fraction between techniques (EA–PA) for the March 3 (March 7) case is $\approx 0.7\% \pm 5.7\% (\approx 4.7\% \pm 3.1\%)$, while the ratio of chord lengths, EA/PA, is $\approx 3 (\approx 1.6)$ for March 3 (March 7). This suggests that the ellipse technique may overestimate cloud coverage.

In both cases, DSTOC predicts less downwelling shortwave radiation (DWSR) at the surface than CRM, due to more photons scattering between clouds, and longer path lengths (Fig. 2). There is also less absorption (ABS) by DSTOC and greater upwelling shortwave radiation (UPSR) at the top-of-atmosphere, due to some of the scattered photons exiting to space. Both DSTOC and CRM are quite sensitive to the method for calculating cloud fraction (i.e., using EA or PA), most notably in the UPSR with a mean difference of ≈ 30 and $\approx 40\ \mathrm{W \cdot m^{-2}}$, respectively. This mean difference is slightly less for UPSR and nearly negligible for ABS. The effect is also present in the March 3 data but to a lesser extent. By contrast, DSTOC is basically insensitive to the method of calculating the characteristic chord length (i.e., from the ellipse or closed CWC contours) similar to results from [18] (not shown). Surprisingly, for the scenes we studied, the magnitude of the difference in fluxes resulting from changing the cloud fraction technique is of the same order or larger than that due to using one model versus the other.

Both models are sensitive to changes in resolution of the simulated cloud fields. This is primarily due to the variation seen in the Liquid Water Path (LWP) and cloud fraction which is input to the models (Fig. 3). The largest difference between DWSR in the CRM runs is $\approx 150\ \mathrm{W \cdot m^{-2}}$ (between the 40- and 160-km runs). The largest difference in the DSTOC runs is $\approx 100 - 120\ \mathrm{W \cdot m^{-2}}$ (again between the 40- and 160-km resolutions). For the scenes examined, although there is strong sensitivity to resolution, there is no clear relationship between resolution and model produced flux in either model.

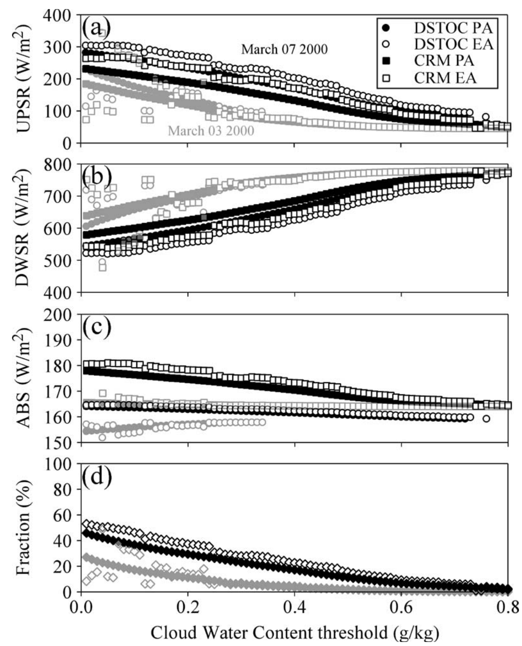

Fig. 2. (a) Upwelling shortwave radiative flux at the top of the atmosphere, (b) downwelling shortwave radiative flux at the surface, (c) absorption, and (d) could fraction for (black) March 7, 2000 and (gray) March 3, 2000 using (closed symbols) PA and (open symbols) EA.

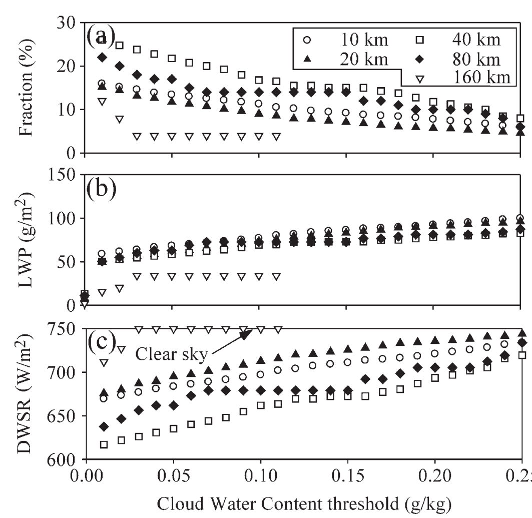

Fig. 3. (a) Cloud fraction, (b) LWP, and (c) DSTOC DWSR calculated using PA for March 3, 2000 at different horizontal grid spacing.

V. CONCLUSION AND RECOMMENDATIONS

This letter has indicated that it is possible to derive the necessary statistics from RAMS cloud fields to run a stochastic RT model. Two methods of calculating cloud fraction and cloud chord length were explored. The stochastic model is shown to be insensitive to the method of calculating cloud chord length, even though the methods differ in chord length values by as much as a factor of four. Both CRM and DSTOC are very sensitive to the method of calculating cloud fraction, as each method produced significantly different cloud fraction amounts.

The sensitivity of the predicted radiation to the resolution of the simulated cloud field was evaluated. Although there is strong sensitivity, no simple relationship is deduced. Further study is necessary to fully investigate this issue. Additional cases will be explored to develop the relationship between grid averaged dynamics and calculated cloud fraction and cloud chord lengths.

This project is a preliminary attempt to develop a framework for assessing the way to optimally incorporate more sophisticated treatments of cloud variability into climate models. More work is needed to build on these efforts and to answer the associated science questions. For example, a similar comparison should be employed over a much wider range of cloud scenes (e.g., stratiform, convective, summer, winter, over land, over ocean, multilayer clouds, etc.) drawn from high-resolution mesoscale model simulations. Moreover, the differences in radiative fluxes calculated at all levels of sophistication must also be evaluated in terms of the dynamical and thermodynamical drivers of the cloud variability.

This additional development of our approach will allow us to identify how (if at all) the differences between the various sets of fluxes are related to the differences in synoptic regime, atmospheric dynamical processes, and cloud type between the cases, and identify any insights into the potential impact of cloud variability on GCM-scale radiative fluxes, when and where the representation of such variability might be needed or desirable, and the dependence of this impact on the underlying resolution of the cloud field and the cloud-processing dynamics and thermodynamics.

In short, we believe that linking a high-resolution 3-D atmospheric numerical model to a sophisticated RT scheme with the capability to take full advantage of the additional information on cloud spatial variability provided will prove to be a highly effective methodology for investigating fundamental questions of RT through a cloudy atmosphere and aiding parameterization development. Following our basic merging of the modeling tools and investigation of the preliminary research questions, as proposed here, we expect to expand the scope of this letter to encompass the examples discussed in this letter and beyond.

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